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HEXADECAPOLE TRANSITION MOMENTS IN STRONGLY DEFORMED NUCLEI AND THE VALIDITY OF THE sd-BOSON APPROXIMATION IN THE IBA

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The low-lying spectrum of ^{156}Gd up to 3 MeV has been investigated with proton scattering at E_p = 40 MeV. Considerable hexadecapole transition strength is found at E_x > 1.5 MeV indicating the necessity for the inclusion of a g-boson in the IBA to explain properties of states above this energy. An IBA calculation including a g-boson reproduces qualitatively the experimentally observed hexadecapole transition strength below 3 MeV.

The success of the interacting boson approximation model (IBA) in describing the properties of low-lying collective states of even–even medium-mass and heavy nuclei has been demonstrated by a large number of publications in recent years. In a series of comprehensive articles [1], Arima and Iachello have shown that a general hamiltonian describing a system of s- and d-bosons [SU(6) model] has for different choices of the boson energies and boson–boson interactions the limits: SU(5), SU(3) and O(6). These correspond, respectively, to the conventional vibrational [2], rotational [2] and γ-unstable [3] models. Extensions of the IBA to include other degrees of freedom have already been considered in the past, e.g. the inclusion of the f-boson is necessary to explain [1] negative-parity levels. More recently, the problem of the coupling of non-collective two-(quasi-) particle states to the collective s- and d-bosons, has been treated [4] and the inclusion of the g-boson was investigated [5] in a perturbational approach.

In ^{156}Gd which can be described as a well-deformed nucleus, extensive studies [6] indicated the existence of $K^\pi = 0^+$ and $K^\pi = 4^+$ bands starting at E_x = 1168 keV and 1511 keV, respectively. These bands cannot be described in the IBA by considering only s- and d-bosons. While the $K^\pi = 0^+$ band is probably associated with the subshell closure at proton number $Z = 64$ in the 50–82 shell [7], the $K^\pi = 4^+$ band requires [8] the addition of the hexadecapole degree of freedom (g-boson). Whereas the addition of an f-boson may have little influence on the positive-parity levels below 2 MeV, the situation could be different, in general, for a g-boson. Thus the important question arises: what is the extent of the perturbation [9] caused by the g-boson on the low-lying collective spectrum as calculated in the sd-boson approximation?

To answer this question, we have studied inelastic proton scattering from ^{156}Gd. Inelastic proton [10] and deuteron [11] scattering experiments at lower bombarding energies were performed before the present work. While a wealth of information about the low-lying bands of ^{156}Gd is available [6] (most of the states below 2 MeV have assigned spins and parities) very little is known [6,10,11] about the distribution of octupole and hexadecapole strengths. This is true for the rare-earth nuclei in general, although the hexadecapole deformations of the 4^+ states of the ground-state bands (g.s.b.) for many of them have been known [12] for a long time. In this letter we present results for the hexadecapole strength distribution and compare these with the results of an IBA calculation in-

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cluding a g-boson.

A self-supporting ^{156}Gd target of 1.2 mg/cm^2 thickness was bombarded with a 40 MeV analysed beam of protons from the KVI cyclotron. Scattered protons were detected using the QMG/2 magnetic spectrograph [13] with an overall energy resolution of 24 keV. Angular distributions were measured from $\theta_{lab} = 12°$ to 60° mainly in steps of 1.5°. The solid angle subtended by the spectrograph was 1.82 msr with an opening angle in the reaction plane of 1°.

In fig. 1 a ^{156}Gd(p, p′) spectrum taken at $\theta_{lab} = 31.5°$ is shown. In addition to the states of the g.s.-, β- and γ-bands, many states are observed up to ≈3 MeV. Peak-fitting analysis was performed for these states. Absolute differential cross sections were obtained by normalizing the elastic scattering cross section to an optical model calculation using parameters of ref. [14]. The uncertainty in the absolute cross sections due to this analysis is estimated to be less than 10%.

In fig. 2 differential cross sections for the 4^+ states of the g.s.- and γ-bands are shown. The 4^+_{gs} state of the g.s.b. is obviously not fitted by the DWBA calculation shown as a dashed line. A CC calculation in the symmetric rotor model searching for the deformation parameters was performed using the program ECIS [15] including the 0^+_{gs}, 2^+_{gs}, 4^+_{gs} and 6^+_{gs} states. The search resulted in a rather good fit to the 4^+_{gs} state (solid line) with $\beta_4 = 0.059$. A reasonable fit could also be obtained with a smaller β_4 by increasing the contribution of the $\int V(r, \theta, \phi, \beta_2)\, Y_0^4(\theta, \phi)\, d\Omega$ term which corresponds in the IBA to the $[d^\dagger \tilde{d}]^{(4)}$ term.

The 4^+_γ state at E_x = 1.355 MeV was not resolved from a 1^- state at 1.366 MeV [16]. At forward angles there is a large contribution from this 1^- state. This is clear from comparing with the dotted curve which represents the experimental data [17] for the known [6,16] 1^- state at E_x = 1.242 MeV. The other curves are the result of CC calculations [18] in the asymmetric rotor model including [19] a hexadecapole vibrational term for the 4^+_γ state. The dashed curve is for β_4 = 0.

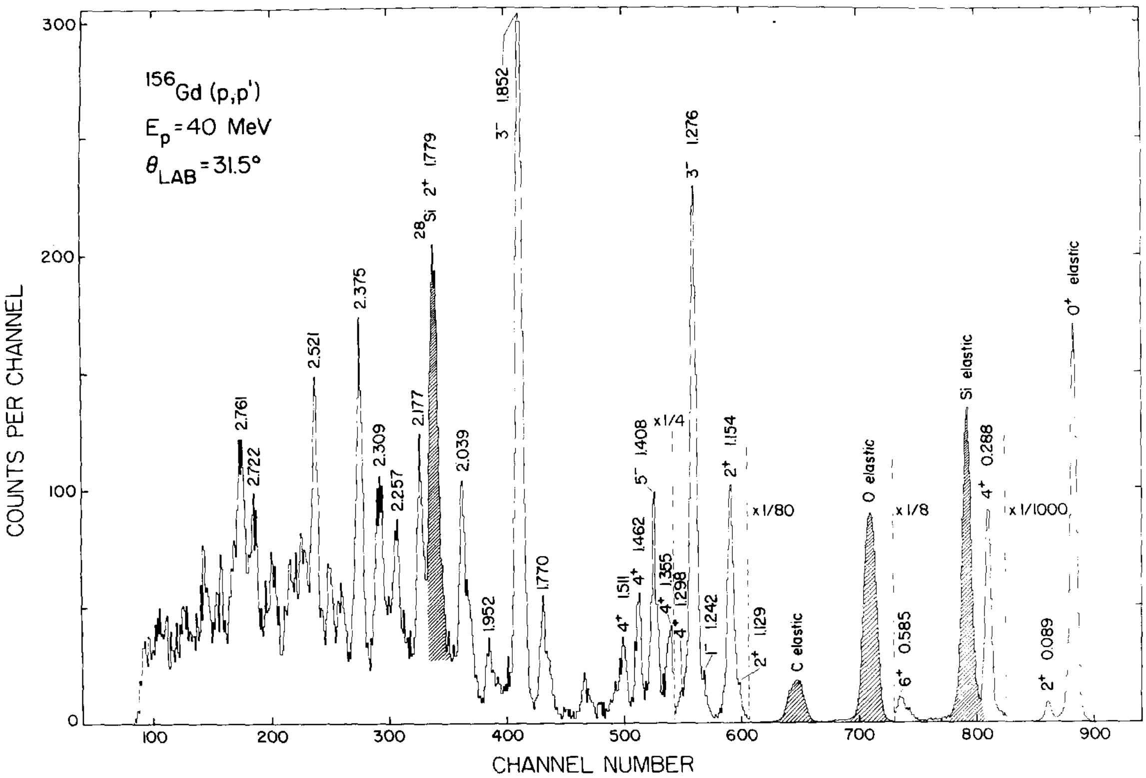

Fig. 1. A ^{156}Gd(p, p′) spectrum taken at θ_{lab} = 31.5° and E_p = 40 MeV. Well-known states are labelled by their energy and J^π. Contaminant peaks are indicated.

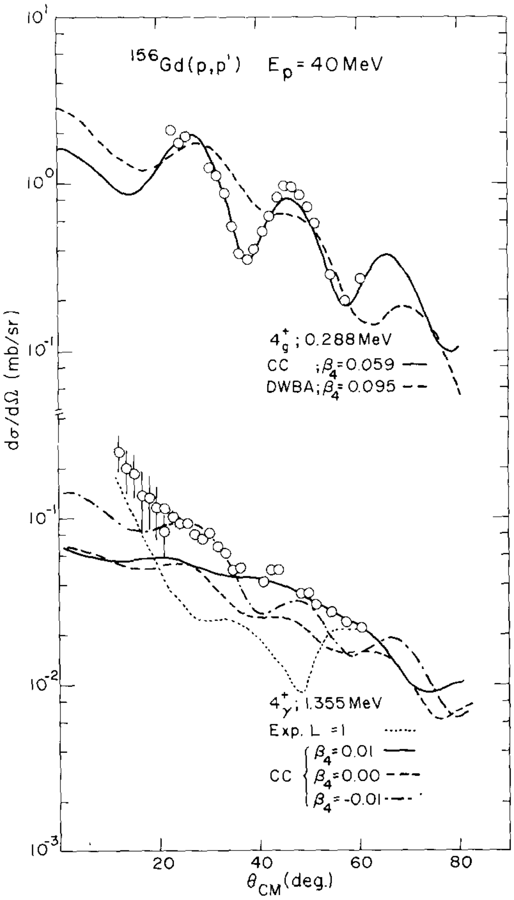

Fig. 2. Angular distributions for the 4^+ states of the g.s.- and the γ-bands. The meaning of the curves is indicated in the figure and explained in the text.

The solid and dashed–dotted curves are for β_4 = 0.01 and −0.01, respectively, and represent upper limit fits to the 4^+_γ state since for a total fit one should also include the contribution of the 1^- state.

In fig. 3, data for known and possible 4^+ states are shown. In this figure, solid, dashed and dashed–dotted curves represent DWBA calculations for L = 4, 3 and 5 transitions, respectively. Many of these states were fitted by L = 4 DWBA curves and thus assigned $J^\pi = 4^+$. Peaks at 1.952, 2.039 and 2.093 MeV are slightly better fitted by an L = 4 DWBA curve although the other indicated alternatives are probable.

The 4^+_β state of the β-band lies at the tail of a very strong 3^- state at 1.276 MeV which can contribute to the cross section of the 4^+_β state as indicated by the L = 3 curve. The L = 4 curve drawn for β_4 = 0.03 represents the upper limit of the L = 4 contribution.

Results are listed in table 1. The excitation energies, spins and parities are obtained from refs. [6] and [16] for known states, otherwise they are the results of the present work. Hexadecapole deformation parameters (β_4) which can be associated with a g-boson excitation are listed in column 3. These were used to obtain the hexadecapole transition rates in single-particle units (s.p.u.) listed in column 4. Contributions to the hexadecapole transition rates of the 4^+ states of the g.s.- and γ-bands from the $\int V(r,\theta,\phi,\beta_2,\gamma)\, Y^4_\mu(\theta,\phi)\, d\Omega$ term, corresponding in the IBA to the $[d^\dagger \tilde{d}]^{(4)}$ term, have not been included in column 4. For the 4^+_{gs} state, with β_2 = 0.274 for the g.s.b., this is equal to 5.3 s.p.u. [i.e. in total $B(E4) \approx 23$ s.p.u.].

Of the g.s.-, β- and γ-bands, only the 4^+_{gs} state seems to have large g-boson strength. This, however, may be an artifact of the method of CC analysis (symmetric rotor model) as was mentioned earlier. In that respect, it would be of interest to compare the experimental data for the g.s.b. with the predictions of a CC calculation using matrix elements from an IBA calculation where the contribution of the $[d^\dagger \tilde{d}]^{(4)}$ term could differ appreciably from that of the symmetric rotor limit. At any rate, it is apparent from table 1 that experimentally at least 65% of the g-boson strength is located above 1.46 MeV. This percentage could increase if all uncertain g-boson strength is taken into account and/or the g-boson strength contribution to the 4^+_{gs} state turns out to be smaller because of a more enhanced $[d^\dagger \tilde{d}]^{(4)}$ contribution than predicted with the symmetric rotor model.

In order to understand this hexadecapole strength distribution, an IBA calculation was performed including a g-boson in addition to the s- and d-bosons. The details of this calculation will be published elsewhere [8]. Here only the hexadecapole moment distribution will be considered. In table 1, the excitation energies (column 5) and hexadecapole transition rates ($[d^\dagger \tilde{d}]^{(4)}$ contribution in column 6, $[g^\dagger \tilde{s}]^{(4)}$ in column 7) of all predicted 4^+ states below 3 MeV are listed. The calculated g-boson strength is concentrated in a few 4^+ states which belong to the various bands arising from the coupling of a g-boson to the core of s- and d-bosons. The experimental g-boson strength displays more fragmentation than the theoretically predicted one. In one respect, however, the theoretical predictions qualitatively describe the experimental data: the

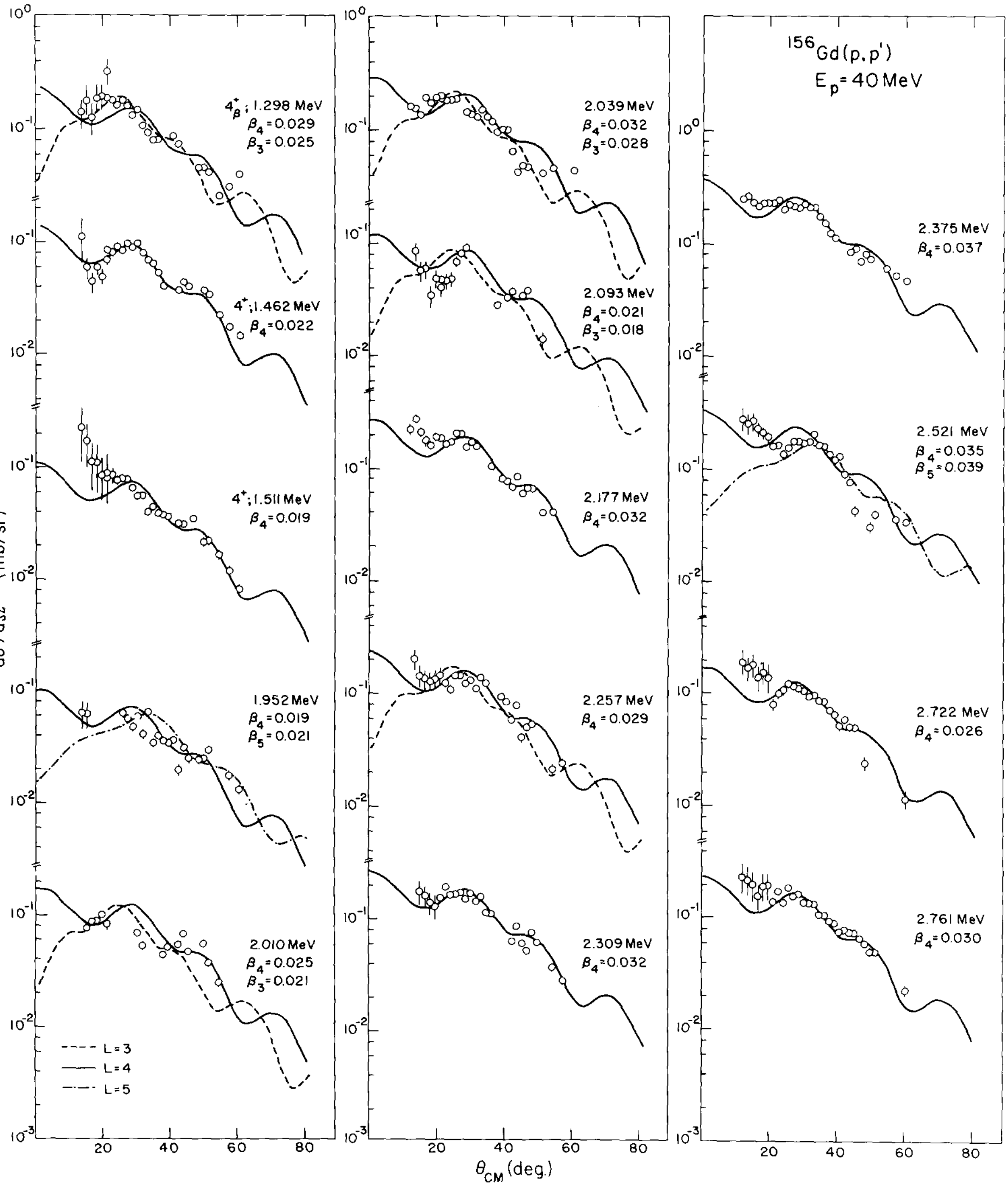

Fig. 3. Angular distributions of known and possible L = 4 transitions. Solid, dashed and dashed–dotted curves are results of DWBA calculations for L = 4, 3 and 5, respectively. Deformation parameters needed to obtain the fits are indicated in the figure.

Table 1
Experimental and theoretical hexadecapole transition moments of low-lying 4^+ states in ^{156}Gd.

Experimental			Theoretical			
E_x (MeV)	J^π	β_4	$\|\langle M(E4)\rangle\|^2$ (s.p.u.) [d]	E_x (MeV)	$\|\langle[d^\dagger\tilde{d}]^4\rangle\|^2$ [f]	$\|\langle[g^\dagger\tilde{s}]^4\rangle\|^2$ [f]
0.288 [a]	4^+_{gs}	0.059 [c]	6.18	0.267	57.0	0.026
1.298 [a]	4^+_β	≤0.03	≤1.5	1.278	1.46	
1.355 [a]	4^+_γ	≤0.01 [c]	≤0.18	1.346	3.03	0.038
1.462 [a]	4^+	0.022	0.86			
1.511 [a]	4^+	0.019	0.64	1.511	0.001	9.51
1.952 [b]	$4^+ (5^-)$	0.019	(0.64) [e]	1.979	0.123	0.064
2.010 [b]	$(4^+, 3^-)$	0.025	(1.11) [e]			
2.039 [b]	$4^+ (3^-)$	0.032	(1.82) [e]	2.043	0.022	11.5
2.093 [b]	$4^+ (3^-)$	0.021	(0.78) [e]	2.097	0.068	0.054
2.177 [b]	4^+	0.032	1.82	2.204	0.085	0.022
2.257 [b]	4^+	0.029	1.49			
2.309 [b]	4^+	0.032	1.82	2.333	0.018	7.40
2.375 [b]	4^+	0.037	2.43	2.407	0.058	0.008
2.521 [b]	$(4^+, 5^-)$	0.035	(2.17) [e]	2.511		0.003
2.722 [b]	4^+	0.026	1.20	2.647		0.001
2.761 [b]	4^+	0.030	1.60	2.660		0.109
				2.720		
				2.908	0.001	0.015
				2.992		0.009

a) Energies, spins and parities from refs. [6,16].
b) Energies obtained from this experiment correct to better than 5 keV, since for known levels our deduced energies were within 5 keV from their adopted [6,16] values.
c) β_4 obtained from CC analysis (see text).
d) The E_4 transition strength was calculated for uniform density and compared with the single-particle estimate (s.p.u.) $B_{sp}(EL\uparrow) = [(2L+1)/4\pi][3/(3+L)]^2 R^{2L}$, $R = 1.2\ A^{1/3}$ fm. If instead a Fermi distribution is considered, the numbers in this column should be multiplied by 2.45.
e) Numbers in brackets represent uncertain hexadecapole strength.
f) Relative units.

concentration of the g-boson strength above 1.5 MeV. A better qualitative agreement is obtained between theory and experiment if the g-boson strength distribution is considered in 300 keV bins.

The shortcoming of the IBA calculation including a g-boson in explaining the fragmentation of the hexadecapole strength could possibly be remedied by increasing the interaction strength of the hamiltonian which mixes the g-boson states with the sd-boson states. However, this should be studied in connection with the E2 transitions from the $K^\pi = 4^+$ band at 1.511 MeV to the g.s.-, β- and γ-bands, from which the interaction strength presently used has been derived [8]. Removing the restriction of the g-boson number to one and increasing the number of quasiparticle excitations should also be investigated. In this connection, it would be interesting to see whether increasing the interaction strength and/or the number of g-bosons would strongly affect the hexadecapole transition of the 4^+_g. It is hopefully with such experimental studies as reported here that insight into these basic questions connected with the IBA formalism could be gained.

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